

Outflowing disk winds in B[e] Supergiants

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Abstract. The effects of rapid rotation and bi-stability upon the density contrast between the equatorial and polar directions of a B[e] supergiant are investigated. Based on a new slow solution for different high rotational radiation-driven winds and the fact that bi-stability allows a change in the line-force parameters (α , k , and δ), the equatorial densities are about 10^2 – 10^3 times higher than the polar ones. These values are in qualitative agreement with the observations. This calculation also permits to obtain the aperture angle of the disk.

1. Introduction

Stellar winds play an important role in the evolution and the observed physical properties of B[e] supergiants. Most of these early-type objects are IRAS sources. They show an optical spectrum dominated by metallic emission lines of permitted and forbidden transitions from singly ionized elements with FWHM ~ 100 km s $^{-1}$. Their UV spectrum shows lines of superionized elements with large Doppler shifts.

The peculiar spectrum of B[e] supergiants has been interpreted by the presence of a slowly outflowing equatorial disk and a normal fast polar wind (Zickgraf et al. 1985). In order to explain the formation of this two-component radiation-driven wind around early-type stars, Lamers & Pauldrach (1991) have introduced the bi-stability mechanism. Vink et al. (1999) have shown that the bi-stability mechanism induced by rotation in line driven-winds is due to the radiative acceleration by iron, caused by the recombination of Fe IV to Fe III.

Pelupessy et al. (2000) have calculated the density contrast (the ratio between equatorial and polar densities) in a B[e] supergiant for rotationally-induced bi-stability models applying multi-scattering line-force parameters above and below the critical temperature of the bi-stability jump ($T_{\text{eff}} = 25,000$ K). The models were computed considering values of $\Omega = v_{\text{rot}}/v_{\text{brkup}} \lesssim 0.6$, where v_{rot} is the equatorial rotational speed and v_{brkup} is the break-up speed, and the calculated ratio between equatorial and polar densities was about ~ 10 , a factor 10 times smaller than Bjorkman's (1998) calculations.

However, B[e] supergiants represent a post-main sequence evolutionary phase of massive stars and are located near the Eddington limit (Zickgraf et

al. 1986). Then, critical rotation speed is reached at a much lower stellar rotational speed. Velocities of about 200 km s^{-1} would make the star rotate sufficiently close to the break-up speed to produce observable effects. Consequently, the wind characteristics near the equator are expected to differ from the polar wind.

Curé (2004) proved that the standard solution (hereafter the fast solution) of the modified CAK wind model (hereafter m-CAK, Friend & Abbott 1986) vanishes for rotational speeds of $\sim 0.7 - 0.8 v_{\text{brkup}}$, and there exists a new solution that is much denser and slower than the known standard m-CAK solution. We will call it hereafter the *slow* solution.

The aim of this work is to re-investigate the formation of an equatorial disk-wind for rapidly rotating B[e] supergiants, taking into account: 1) the fast and slow solutions of rotating radiation-driven winds that depend on the assumed rotational speed and 2) bi-stability line-force parameters.

In section 2. we show the density contrasts for a B[e] supergiant that result from m-CAK models with fast and slow solutions. The calculations of the aperture angle of the disk is presented in section 3. The discussion and the conclusions are presented in sections 4. and 5., respectively.

2. Wind model results

In order to investigate the influence of the rotation and the bi-stability jump on forming a disk-wind, we solve the non-linear momentum equation for the m-CAK wind in both polar and equatorial directions. Details and calculation methods used here are found in Curé (2004). Since there is no calculation of the line-force parameters considering the slow solution found by Curé (2004), we adopt the line-force parameters, α and k , published by Pelupessy et al. (2000) that were calculated for both sides of the bi-stability jump. We do not include the parameter δ determined by Abbott (1982) since this parameter has very small effects on the density ratio ρ_e/ρ_p (Curé et al. 2005a). The line-force parameters are summarized in Table 1.

We model a B[e] supergiant star with following parameters: $T_{\text{eff}} = 25,000 \text{ K}$, $M/M_{\odot} = 30$, $\log L/L_{\odot} = 6$ and solar abundance. For the lower boundary condition for polar and equatorial directions, we set a constant value for the density in the photosphere, $\rho_p(R_*) = 5 \times 10^{-10} \text{ gr cm}^{-3}$ (de Araujo & de Freitas-Pacheco 1989).

Table 1. Bi-stability line force parameters

T [K]	α	k	δ
30,000	0.65	0.06	0
17,500	0.45	0.57	0

In this work we have not taken into account either the change in the shape of the star or gravity darkening (von Zeipel effect) or the modification of the finite-disk correction factor due to the rotation (Cranmer & Owocki 1995 eq. [26], Pelupessy et al. 2000). However, we expect that these effects may have a small influence on the fast solution since we have not found large difference between our models (Curé, et al. 2005a) and Pelupessy et al. (2000) results.

Table 2. Parameters calculated for a star with $T_{\text{eff}} = 25,000$ K, $\log g = 2.5$ applying m-CAK models: Rotational parameter Ω , terminal velocity, v_{∞} (km s^{-1}) and r_c/R_* , the location of the critical point.

	Ω	v_{∞}	r_c/R_*
<i>pole</i>	0.0	679	1.14
<i>equator</i> ^a	0.6	253	1.19
<i>equator</i>	0.7	178	4.19
<i>equator</i>	0.8	165	5.57
<i>equator</i>	0.9	153	6.43
<i>equator</i>	0.95	147	6.78

^a Fast solution

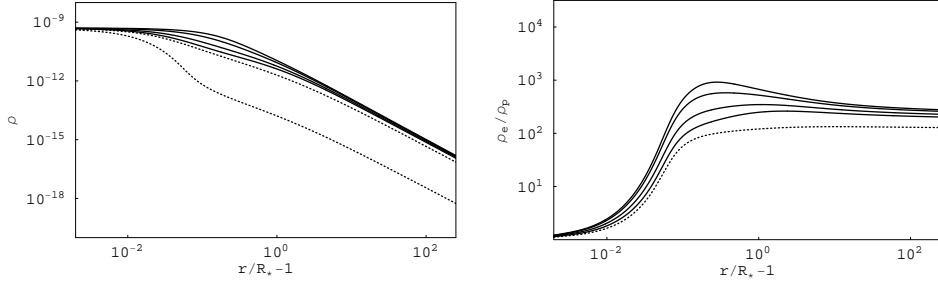


Figure 1. Left: density (in g cm^{-3}) versus $r/R_* - 1$. Polar density is in dotted-line; equatorial density for $\Omega = 0.6$ (fast solution) is also in dotted-line and equatorial densities (slow solutions) for $\Omega = 0.7, 0.8, 0.9, 0.95$ are in continuous-line, the higher is Ω , the higher is the density. Right: density contrast versus $r/R_* - 1$, dotted-line is for $\Omega = 0.6$ (fast solution) and continuous-lines are for (slow solutions) $\Omega = 0.7, 0.8, 0.9, 0.95$. The higher is Ω , the higher is the density contrast.

Figure 1 illustrates density distributions and density contrasts for different rotational speed computed for m-CAK wind models and the set of line-force parameters given in Table 1.

Due to the fact that the existence of the fast or slow solution depends on the rotational speed, we also show in Figure 1 the density profiles obtained; fast solution for $\Omega = 0.6$ and slow solutions for higher rotational speeds, $\Omega = 0.7, 0.8, 0.9, 0.95$.

The fast solution, which is shown in Figure 1 in dotted-line, yields to a density distribution that is lower than the densities attained with the slow solutions (continuous-lines) and higher than the polar density ($\Omega = 0$). We obtain a density contrast of some hundreds for almost all the wind. The increase in the density contrast in the region close to the photosphere is due to the centrifugal force and the consequently higher mass-loss rate of the fast solution when rotation is included (Friend & Abbott 1986).

Density contrasts reach values of around some hundreds to thousand for radii less than $\sim 2R_*$ and an approximately value of some hundreds is maintained by the wind up to hundreds of stellar radii, almost independently of Ω . This

result concerning the disk behaviour is in qualitative agreement with the values estimated from observations by Zickgraf et al. (1985, 1986, 1992), Zickgraf (1998), Oudmaijer et al. (1998) and Bjorkman (1998).

3. Aperture angle of the wind

In order to know the semi-aperture angle of the disk-wind, we start from the equator and calculate up to which angle (from the equator) the slow solution exists, for greater values of the angle, only the fast solution exists. Therefore, we define the semi-aperture angle of the disk the *last* possible angle when the slow solution exists. Table 3 summarized the semi-aperture angle for the star used here for different assumed rotational speeds. The semi-aperture angle of the disk is larger as the rotational velocity increases.

Table 3. The semi-aperture angle of the disk

Ω	$\Theta_{\delta=0}$
0.7	25
0.75	32
0.8	38
0.85	42
0.9	45
0.95	48

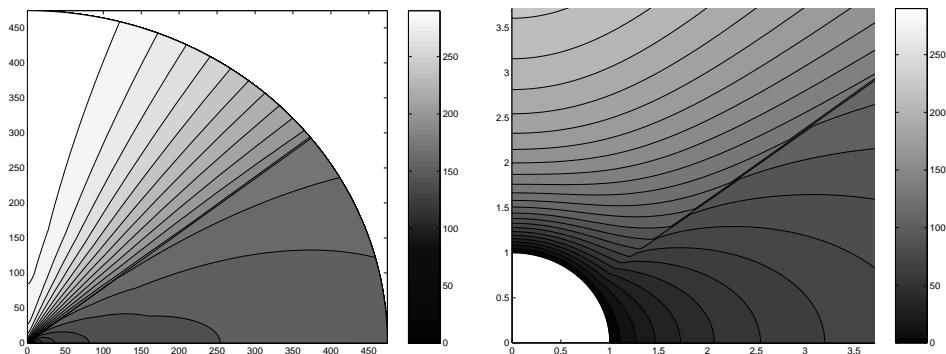


Figure 2. Left: velocity profile (in km s^{-1}) versus r/R_* for $\Omega = 0.8$. The lines denote iso-contour velocities. Right: Same as Left, but a zoom near the photosphere.

4. Discussion

We want to stress the importance of the combined effect of slow and fast solutions with bi-stable line-force parameters in forming an outflowing disk wind in B[e] supergiants. Density contrasts of the order of some 10^2 up to large distances

from the star are attained. This theoretical value is in qualitative agreement with the values derived from the observations of the order of 10^2 – 10^3 (Zickgraf et al. 1989, Zickgraf 1998 and references therein, Bjorkman 1998). The half-opening angle of the gaseous disk increases with the rotational velocity and its values are in the range 25 to 50 degrees. This angle depends strongly on the value of the star's gravity, the greater is the gravity ($\log g$) the smaller is the disk angle (Curé et al. 2005b).

Previous simulations of gaseous disk formation in rotating radiation-driven winds induced by bi-stability have underestimated the density contrast, mainly due to: a) The use of a β -field (with $\beta = 1$, Lamers & Pauldrach 1991) to describe the wind velocity profile, even for high rotational speeds where this approximation fails (Curé 2004), and b) Pelupessy et al. (2000) calculations, based in the fast solutions, were restricted to values of $\Omega \leq 0.6$ and these rotation values are not high enough to develop a dense disk.

A dense disk is formed when the slow solution starts to exist. For our test star, this occurs (numerically) for $\Omega \geq 0.7$. This condition is in qualitative agreement with the estimation of $0.74 \leq \Omega \leq 0.79$ by Zickgraf (1998) in order to reproduce observable effects in the structure of stellar winds. However, observational rotation speeds of B[e] supergiants have high uncertainties, because only a few stars show photospheric absorption lines appropriate for the measurements of $V \sin(i)$. The inferred observational value of Ω lies in the range 0.4–0.7 (Zickgraf 1998).

Since most of the B[e] supergiants in the H–R Diagram are located below the bi-stability jump temperature (25,000K), in our conception, the theoretical explanation for the existence of a two-component wind model (Zickgraf et al. 1985) is due to the nature of the solutions of rapidly rotating radiation-driven wind. The change (jump) from the fast solution to the slow solution at some latitude yields to a two-component wind, where each solution structure has its own set of line-force parameters. This picture would be remarked for cases when the bi-stability jump is present.

The semi-aperture angle of the disk is quite large when the star approaches to the limit of rotation velocity but this angle defines the gaseous structure. However, if a hot dust disk structure develops the dust disk would present a high concentration towards the equatorial plane.

Another important aspect to remark is the scarcity of self-consistent calculations of line-force parameters k , α , δ for the m-CAK fast solution and the lack of calculations for our slow solution. The uncertainty in the values of the parameters is reflected in the value of the terminal velocity, mass loss rate, as well as in the density contrast. Specifically, the predicted terminal velocities, see Table 2 are about two times greater than values inferred by observations (see Table [16] from Zickgraf 1998).

Therefore our results that combine fast and slow wind solutions are a first approximation to re-investigate disk formation in high rotating stars with radiation-driven winds. A detailed wind model needs a self-consistent line-force parameter calculations for both fast and slow solutions for a wind consisting of gas and dust components.

5. Conclusions

We have revisited radiative driven wind models for a rapidly rotating B[e] supergiant ($\Omega \gtrsim 0.6$) assuming a change in the line-force parameters due to the bi-stability jump. The existence of slow and fast solutions in the model predicts density contrasts which are of the order of $10^2 - 10^3$ near the stellar surface ($r \lesssim 2 R_*$), while outside they fall to values of about some 10^2 and the disk extends

up to ~ 100 stellar radii. We estimate a half-opening angle of the gaseous disk is about 40 degree for $\Omega = 0.8$.

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